FRICTION STIR WELDING PARAMETERS FOR AA6351 ALUMINUM ALLOY USING $AgNO_3$ NANO COATINGS: A COMPARATIVE ANALYSIS

T. Vijaya Kumar, Dr. PVR. Ravindra Reddy, Dr. A. Krishnaiah

Research Scholar,Department of Mechanical Engineering
Osmania University, Hyderabad

Professor,Mechanical Engg. Dept. CBIT

Sr. Professor,Department of Mechanical Engineering
University College of Engineering
Osmania University, Hyderabad

Abstract:
Aluminum alloys find extensive use in aeronautical and structural applications where Friction Stir Welding's (FSW) excellent mechanical qualities and efficiency make it a popular choice for solid-state joining. Weld quality of AA6351 aluminum alloy with and without silver nitrate ($AgNO_3$) Nano coating is examined in this work, along with the effect of important FSW process parameters. Finding the ideal welding conditions that improve fatigue resistance, hardness, and tensile strength using the Taguchi L27 experimental design is the main goal.This was the highest welding speed ever recorded in the experiments. The results showed that for each material, the best parameter combinations at a high speed friction stir window were proposed by the analysis. Tool pin profile, welding speed, and tool rotating speed were the chosen characteristics, and each was assessed at three separate levels.To determine how the application of AgNO3 Nano coatings affected the welds, a number of samples were tested. Testing for tensile strength, hardness, and microstructural examination with optical and scanning electron microscopy (SEM) were subsequently performed on the welded samples. As an additional focus, this research looks into the possibility of optimizing the FSW characteristics for AA6351 aluminum alloy by coating nanoparticles with AgNO3. Testing for tensile strength, hardness, and fatigue were all part of the mechanical property evaluation process. Welding AA6351 aluminum alloy plates under different process conditions allowed us to undertake our experiments.

1.0 Introduction:

A state-of-the-art solid-state joining technology, Friction Stir Welding (FSW) has become popular for aluminum alloys because it can create welds free of defects and with better mechanical properties (Mishra & Ma, 2005). Because of its superior strength-to-weight ratio, resistance to corrosion, and weldability, AA6351 is the favored aluminum alloy in the aerospace, marine, and automotive sectors (Kumar & Kailas, 2008). To obtain improved weld strength and microstructural refinement, optimizing the process parameters is still a challenge.

To combat this, researchers have looked into using nano-coatings as reinforcing agents to enhance weld properties in recent studies. Researchers have explored the possibility of using silver nitrate ($AgNO_3$) nanoparticles, which have antimicrobial and highly thermal conductivity characteristics, to alter the microstructure of the weld zone and improve its mechanical properties (Zhang et al., 2019). Grain refinement, hardness, and overall weld integrity can be affected by incorporating $AgNO_3$ nano-coatings into the FSW process.

The objective of this research is to improve the quality of welds by optimizing the FSW parameters for AA6351 aluminum alloy with the addition of $AgNO_t$ nano-coatings. The goal of this research is to find the best possible setup for optimizing weld efficiency and mechanical performance by studying important parameters such tool rotating speed, traverse speed, and axial force.

2.0 Research Methodology

This study aimed to improve the quality of welds produced by AA6351 aluminum alloy by optimizing Friction Stir Welding (FSW) parameters using $AgNO_3$ nano-coatings. In order to achieve uniform coverage, AA6351 alloy plates

were coated with AgNO₃ nanoparticles using a uniform deposition approach such dip-coating (Zhang et al., 2019). The FSW process was executed using a CNC-controlled milling machine. The tool pin shape, traverse speed, and tool rotating speed were chosen according to their impact on mechanical qualities and weld strength (Mishra & Ma, 2005). The parameters were systematically optimized using a Taguchi-based Design of Experiments (DOE) approach, which allowed for complete analysis with fewer experimental runs (Kumar & Kailas, 2008). Gupta et al. (2021) used X-Ray Diffraction (XRD) to study phase transformations in the weld zone, tensile and microhardness testing to assess mechanical performance, and Scanning Electron Microscopy (SEM) to study microstructural changes after the weld. In order to optimize FSW based on data, the results were subjected to Analysis of Variance (ANOVA) to identify the most important factors influencing weld quality.
The alloy AA6351 was chosen for friction stir welding of metals that are not compatible with each other. Aluminum's high ductility and excellent strength properties led to its selection, while AA6351 alloy's moderate strength and superior corrosion resistance were major factors.The 100 mm x 100 mm x 6 mm plates were ground using a vertical milling machine.The 6-millimeter-thick metal sheets were cut into 100-millimeter-long and 100-millimeter-wide rectangles. The design matrix utilized was the L27 orthogonal array from the Taguchi design approach. Tool pin profile, axial force, tool traversal speed, and tool rotational speed were the characteristics that were taken into account. You may find the design of experiment matrix and the different parametric levels in the tables.

Table 1 FSW parameters and their levels

Factors	Level 1	Level 2	Level 3
Tool rotational speed, N (rpm)	1000	1500	2000
Tool traversal speed, S (mm/min)	120	150	180
Tool pin profile,	Square	Cylindrical Threaded	Tapered

Using a friction stir welding machine that was developed in-house, a single pass butt weld was created in 6-millimeter-thick aluminum alloy AA6351 plates as part of the experimental procedure. The tool may be rotated at 3000 rpm, an axial load of up to 30 kN can be applied, and the transverse speed can reach 500 mm/min on this machine. The FSW machine's power consumption can be monitored with a wattmeter that is linked to its motors. The necessary dimensions (100 mm × 100 mm) were achieved by utilizing shaper and milling equipment to cut 6 mm thick rolled plates. Afterwards, the Taguchi design matrix was used to produce the various Friction Stir welded joint specimens.

Table 2 FSW process parameters coded run order L27 matrix formation

Run order	Speed(N)	TS(v)	PP(P)
1	1000	120	Square
2	1000	120	Cylindrical threaded
3	1000	120	Tapered
4	1000	150	Square
5	1000	150	Cylindrical threaded
6	1000	150	Tapered
7	1000	180	Square
8	1000	180	Cylindrical threaded
9	1000	180	Tapered
10	1500	120	Square

11	**1500**	**120**	**Cylindrical threaded**
12	**1500**	**120**	**Tapered**
13	**1500**	**150**	**Square**
14	**1500**	**150**	**Cylindrical threaded**
15	**1500**	**150**	**Tapered**
16	**1500**	**180**	**Square**
17	**1500**	**180**	**Cylindrical threaded**
18	**1500**	**180**	**Tapered**
19	**2000**	**120**	**Square**
20	**2000**	**120**	**Cylindrical threaded**
21	**2000**	**120**	**Tapered**
22	**2000**	**150**	**Square**
23	**2000**	**150**	**Cylindrical threaded**
24	**2000**	**150**	**Tapered**
25	**2000**	**180**	**Square**
26	**2000**	**180**	**Cylindrical threaded**
27	**2000**	**180**	**Tapered**

3.0 EXPERIMENTAL SET-UP AND PROCEDURE

Joining the work parts in FS welding required the use of a non-consumable tool. The pieces of metal were bonded while they were still solid, thus there was no melting involved. Because the base material softens around the friction stir welding tool, the revolving tool was able to generate enough heat to melt it.

Figure 1 shows the conventional HMT2EV vertical milling machine that was used for the testing. It has a capacity of 5.5 HP and can rotate at a maximum speed of 2000 rpm.

Figure 1 Photograph Conventional Vertical Milling Machine

The FSW butt joint was achieved by preparing work pieces with dimensions of 100 mm × 100 mm × 6 mm. The welding was done in a normal direction relative to the rolling direction. Three distinct pin profiles—tapered, cylindrical threaded, and square—were utilized by a non-consumable H13 steel tool.

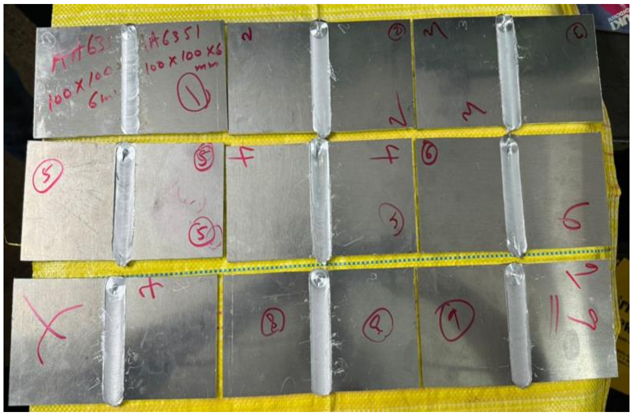


Figure 2 Photograph of fabricated FSW joints according to Taguchi design matrix

The Universal Testing Machine was used to conduct the tensile tests.The necessary steps to prepare the specimen were taken. Every set has its own unique control computer that records the ultimate tensile strength and the elongation at the fracture site. After that, the material's stress-strain curves were made using these numbers.

Figure 3 Photograph of fabricated Friction Stir welded tensile test specimens

In order to measure the hardness at various zones and to investigate the machine's specifications, a semi-Vickers hardness tester was used after the welding was finished (see figure 4).

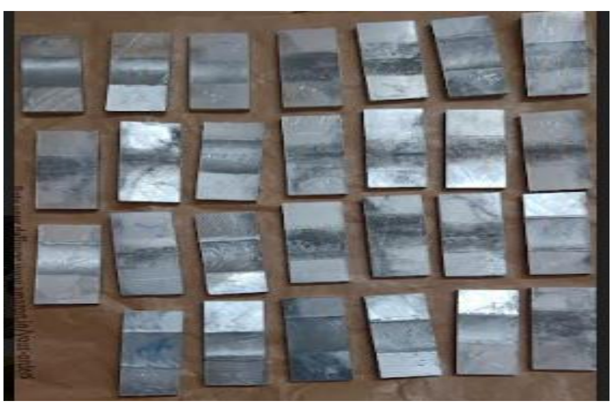


Figure 4 Photograph of fabricated Friction Stir welded hardens test specimens

Analysis of Microstructure

The optical microscope and scanning electron microscope are used to view microstructural characterizations, which are described below.For a detailed look at various surface flaws, pollutants, corrosion materials, and cracks, a scanning electron microscope (SEM) inspection was the way to go. When compared to optical microscopy, scanning electron microscopy (SEM) is superior for rapidly resolving acceptable fractographic features such fatigue striations and tire tracks.

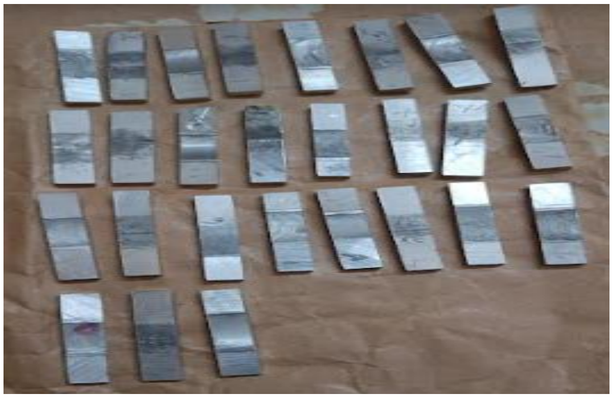


Figure 5 Photograph of fabricated Friction Stir welded Microscopic test specimens (SEM)

An Approach to Nanotechnology and Sample Preparation for Friction Stir Welded Aa6351 Alloy with $AgNO_3$:

A glass beaker, distilled water, a magnetic stirrer, a glass stirring rod, an analytical balance, protective goggles and gloves were all necessary for the successful preparation of the silver nitrate ($AgNO_t$) solution.

Making a Solution of $AgNO_3$

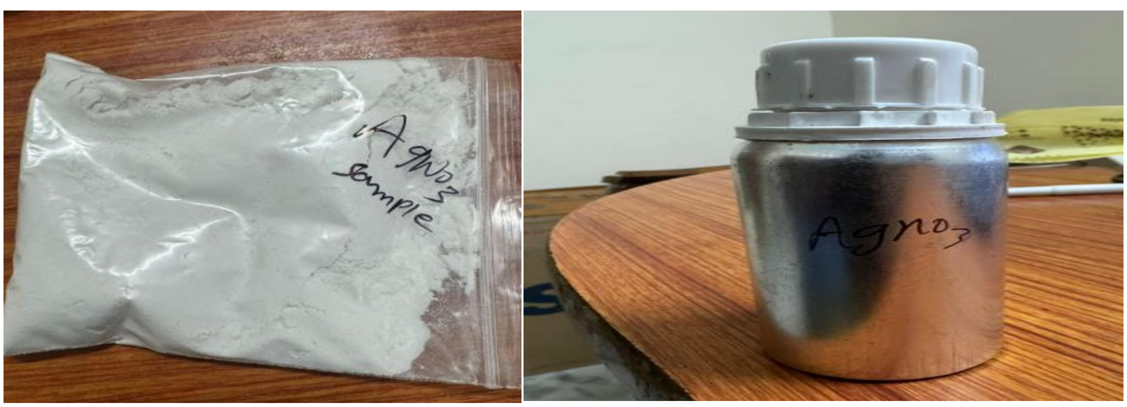
First, the necessary concentration was determined. The required concentration of $AgNO_t$ was 10%, hence 100 mL of distilled water was used to dissolve 10 g of $AgNO_t$. Ten grams of $AgNO_t$ were dissolved in around fifty-nine milliliters of water to make a 1M solution.

2. A fresh glass beaker was set on a magnetic stirrer and filled with the exact volume of distilled water as measured.

3. To make sure the $AgNO_3$ powder dissolved completely, it was added to the water slowly while swirling constantly.

Figure 4 shows that after the $AgNO_3$ was completely dissolved, the solution was moved to a dark amber bottle to avoid light deterioration.14. Applying the Results Experimentally • Welded joints with and without $AgNO_3$ nanoparticles were compared for their mechanical properties, microstructure, and conductivity in order to verify the results of the simulation.

• The dispersion and impact of the silver nanoparticles inside the weld were investigated by means of a scanning electron microscope (SEM).



A) B)

Figure 6 the sample of $AgNO_3$ Nano Particle a) powder and b) solution

Coating technique using a dip

Weld Zone Nano Coating

The Dip coating procedure was used to apply nano coatings on friction stir welded plates. The FSW tool's swirling action effectively dispersed the Nano coating evenly across the weld nugget.

1. Preparation of Samples

The AA6351 aluminum alloy samples utilized as the base material have a reputation for being highly durable and resistant to corrosion, making them ideal for structural uses.

100 mm x 100 mm × 6 mm were the dimensions of the prepared samples.

Friction Stir Welding (FSW): • This solid-state welding method was used to successfully combine two AA6351 plates.

• Comparing to traditional welding procedures, this technology successfully improved mechanical qualities while reducing flaws.

• In the middle of the sample, you could see the weld seam.

Two, Dip Coating with Silver Nitrate ($AgNO_3$)

The AA6351 alloy's surface conductivity, antibacterial qualities, and corrosion resistance were all improved by applying an $AgNO_t$ coating.

• Coating Thickness: A consistent thickness of 0.2 mm (200 microns) was attained by the dip coating.

Procedure for Coating:

First, we prepared the surface by cleaning the FSW samples with acetone and an ultrasonic cleaner to get rid of any contaminants.

2. Immersion: To ensure homogeneous deposition, the samples were submerged in an $AgNO_3$ solution at room temperature (20-25°C) for 11 minutes.

3. Heat Treatment and Drying: The samples that had been coated were dried after immersion in order to get rid of any extra moisture.

The drying process began at room temperature and progressed to an oven set at 50-60°C for 15-30 minutes in order to improve crystallinity and adherence.

Curing Procedure:

• Extra precautions were taken to guarantee correct curing because silver nitrate coatings are light-sensitive.

To make sure the coating was completely dry, the plates were heated to 60 degrees Celsius for 36 minutes in an oven. Table 3 details the process time intervals.

Table 3 Time duration for various dip coating and experimentation process

Step	Duration
Friction Stir Welding	3.6 minutes
Surface Cleaning	22 minutes
$AgNO_3$ Solution Dip	11 minutes
Curing/Drying in Oven	36 minutes

Coating Thickness Measurement

• Examining the Coating's Thickness: Both the pre- and post-coating sample thicknesses were measured using a Vernier caliper.

• Determining the Final Thickness:

The thickness of the base alloy is 6 mm, the thickness of the coating is 0.4 mm (0.2 mm × 2 = 0.4 mm), and the total thickness is 6.4 mm.

A homogeneous $AgNO_3$ coating with increased characteristics was achieved across the entire fabrication and Nano coating process, as illustrated in figure 5, allowing for additional experimental evaluation.

Figure 5 Dip coated AA6351 welded samples

We are getting ready to test the corrosion resistance and mechanical strength of AA6351 friction stir welded (FSW) samples that have been dip-coated with $AgNO_3$ nanoparticles. Silver nanoparticles based on $AgNO_3$ are dip-coated onto the samples to improve the surface characteristics of the welded region. We do a battery of experiments to see how well these coated samples work. We use scanning electron microscopy (SEM) to examine the distribution of elements and the consistency of the coating.

4.0 OPTIMIZATION AND PROCESS PARAMETERS OF FRICTION STIR WELDED AA 6351 ALUMINUM ALLOY

To achieve the desired mechanical characteristics, microstructure, and performance of the welded joints, it is essential to optimize the process parameters in FSW. The heat generation, material flow, and subsequent weld quality are greatly affected by the primary parameters, which include tool rotation speed, transverse speed, and tool design. The hardness and tensile strength of AA 6351 aluminum alloy welds are optimized by adjusting these factors, making them ideal for various industrial uses.The specimens for the tensile tests were meticulously cut from aluminum plates that had been friction stir welded according to the standard ASTM E8. The specimens that had been friction stir welded were subjected to mechanical testing at room temperature on a Universal Testing Machine (with a maximum capacity of 400 kN) in order to determine the UTS, YS, and percentage of elongation. The specimens were subjected to the Vickers micro hardness test on a cross-sectional basis. In the studies, a 250 gf indentation load was applied and a dwell time of 10 seconds was used. For the center cross-section of the welded samples, the hardness profile was recorded. We measured the hardness profile at SZ, TMAZ, HAZ, and BM on both sides of the weld line, starting at the middle of the weld. You can find all of the values in Table 4, which were precisely calculated after each experimental run.

Table 4 Taguchi design matrix and output responses for mechanical properties of Friction Stir welded AA 6351 Al alloy

Experimental run	Factors			Responses			
	Rotational Speed(rpm)	Transverse speed(mm/min)	Tool pin profile	UTS N/mm^2	YS N/mm^2	% Elongation	Hardness (VHN)
1	1000	120	Square	250.59	204.4	2.42	81.78
2	1000	120	Cylindrical threaded	241.49	196.1	2.13	82.45
3	1000	120	Tapered	203.18	167.43	3.41	84.34
4	1000	150	Square	220.23	168.29	2.76	87.98
5	1000	150	Cylindrical threaded	230.13	181.3	2.45	88.45
6	1000	150	Tapered	194.59	151.8	2.04	90
7	1000	180	Square	230.02	182.1	3.1	87.23
8	1000	180	Cylindrical threaded	202.79	159.29	2.93	86.31
9	1000	180	Tapered	246.43	194.49	3.86	91.3
10	1500	120	Square	242.07	201.65	2.96	84.39
11	1500	120	Cylindrical threaded	252.32	190.41	4.68	90.72
12	1500	120	Tapered	218.78	175.9	2.43	88.61
13	1500	150	Square	202.58	154.07	2.7	87.51
14	1500	150	Cylindrical threaded	220.7	150.89	2.34	88.43
15	1500	150	Tapered	231	176.23	3.1	83.67
16	1500	180	Square	239.9	169.98	2.76	85.5
17	1500	180	Cylindrical threaded	238.9	198.78	2.31	87.4
18	1500	180	Tapered	238	183.8	2.18	85.1

19	2000	120	Square	251.23	193.12	2.47	86.1
20	2000	120	Cylindrical threaded	212.79	189.29	2.93	87.31
21	2000	120	Tapered	240.39	198.4	2.32	83.58
22	2000	150	Square	231.49	186.1	2.13	84.35
23	2000	150	Cylindrical threaded	223.18	187.43	2.91	86.34
24	2000	150	Tapered	230.23	178.29	2.86	88.9
25	2000	180	Square	240.13	185.3	2.84	89.3
26	2000	180	Cylindrical threaded	199.2	154.6	2.14	91
27	2000	180	Tapered	200.01	162.1	3.1	86.48

Ultimate Tensile Strength (UTS), Yield Strength (YS), Percentage Elongation (PE), and Hardness (VHN) are some of the mechanical qualities that can be affected by the conditions listed in Table 5.2.

Tool pin profile, transverse speed, and rotational speed were the variables that were examined. The three levels of rotational speed that were examined were 1000 rpm, 1500 rpm, and 2000 rpm, which pertain to the FSW tool's rotational speed during the welding operation. The three measured levels of transverse speed—120 mm/min, 150 mm/min, and 180 mm/min—represent the rate at which the FSW tool travels across the material's surface. The pin's profile on the FSW tool determines how material flows and how much heat is generated while welding. Cylindrical threaded, square, and tapered profiles were all put through their paces.

This study measures four responses: hardness, yield strength, percentage of elongation, and ultimate tensile strength (UTS). A higher UTS number indicates stronger welds since it measures the maximum stress that a material can endure before breaking when stretched or pushed. A higher Young's modulus (YM) indicates that the material can resist greater stresses before permanently deforming; YS is the stress at which plastic deformation starts. The percentage of elongation that a material can withstand before breaking is an indicator of its ductility. The ductility of a material is indicated by its elongation value. A material's hardness (VHN) indicates its resistance to indentation, wear, and deformation; higher hardness levels indicate stronger resistance.

4.1 Microstructure of the welded joints of AA6351 aluminum alloy:

We looked at the microstructure of the AA6351 aluminum alloy welded joints to see how the friction stir welding (FSW) technique changed the material's characteristics. The weld process created separate areas, including the stir zone (SZ), the heat-affected zone (HAZ), and the base metal (BM).

On the other hand, the heat-affected zone displayed evidence of grain coarsening when subjected to moderate temperatures, which could lead to a decrease in mechanical characteristics. Welding parameters such as rotational speed, transverse speed, and tool geometry affected the microstructural features of these areas. In order to achieve the necessary mechanical properties in the welded joints of AA6351 aluminum alloy, it is crucial to optimize the welding parameters, as these findings demonstrate.

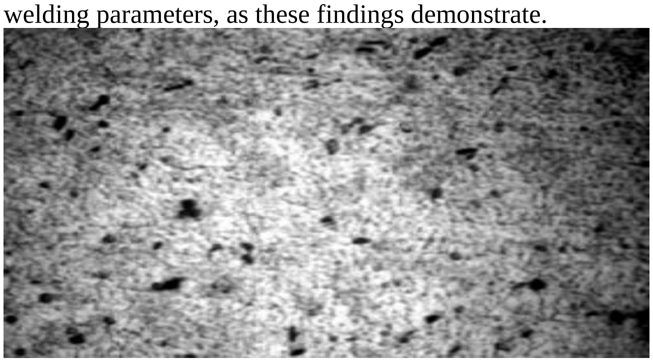


Figure 6 Micro-structures of a AA6351 weld at N: 1000rpm, S: 120 mm/min with square tool

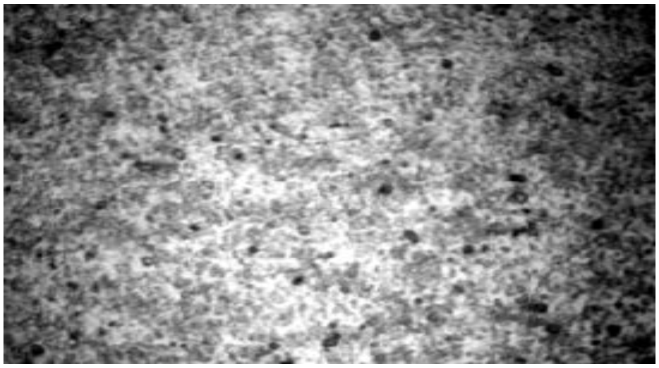


Figure 7 Micro-structures of a AA6351 weld at N: 1500rpm, S: 150 mm/min with square tool

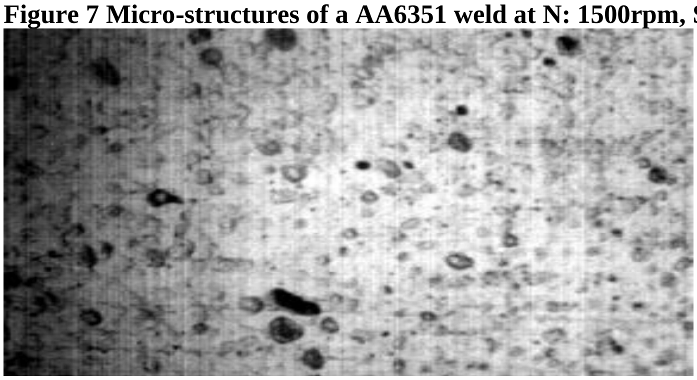


Figure 8 Micro-structures of a AA6351 weld at N: 2000rpm, S: 180 mm/min with square tool

Figure 8 shows that the square tool-processed joint, according to the experimental design's process parameter combinations, had a fine grain structure with grain boundaries in the stir zone or nugget zone. Grain structure is more consistent and voids are less numerous when the tool is spun at 2000 rpm with a feed rate of 180 mm/min.

The microstructural study of the welded connections provides additional evidence that the welding temperature was essentially constant throughout the several experimental runs, supporting this observation. To achieve the desired qualities in the final welded joint, it is essential to have a temperature stable area where the material can flow more consistently and under control.

5.0 ANALYSIS AND OPTIMIZATION OF FRICTION STIR WELDED, SILVER NITRATE ($AgNo_3$) NANO COATED AA6351 ALLOY WITH THROUGH TAGUCHI:

The FSW method generates a great deal of heat as a result of the plastic deformation of the material. The microstructure of the materials that are going to be welded changes as a result of this. To comprehend the impact of heat input or weld process parameters, a thorough examination of the material's microstructure in various weldment zones must be conducted.

By systematically examining the effects of various process parameters on the mechanical and microstructural features of the welded joints, the Taguchi L27 method can be used to optimize friction stir welded (FSW) and silver nitrate (AgNO3) nano-coated AA6351 alloy.

The AA6351 Al Alloy is the foundational material because of its excellent corrosion resistance and mechanical qualities. Material for Coating: Nano-coated silver nitrate (AgNO3), which improves surface hardness, wear resistance, and perhaps antibacterial qualities.

To determine the effect on weld quality, critical factors including tool rotational speed, transverse speed, and tools are changed using FSW parameters.To achieve the highest possible joint tensile strength, the FSW process parameters were fine-tuned.

Applying Nano-Coatings: To determine its impact on the joint's overall performance, the AgNO3 Nano-coating is applied before or after welding, depending on the study's design.

At the weld zone, every welded sample is coated with 0.4mm of silver nitrate (AgNO3).

Improving process robustness and product quality, the Taguchi technique has been successfully employed to overcome the problems of optimal process parameters in single-response production.

To achieve a systematic analysis of the selected elements and their interactions across 27 experimental runs, the Taguchi L27 orthogonal array should be used for the experiment design. Figures below show fabricated and coated AgNO3 samples that were tested for tensile, hardness, and scanning electron microscopy.

Figure 9 Photograph of fabricated Friction Stir welded tensile test specimens with addition of $AgNO_3$ Nano coated

Figure 10 Photograph of fabricated Friction Stir welded hardens test specimens with addition of $AgNO_3$ Nano coated

Figure 11 Photograph of fabricated Friction Stir welded Microscopic test specimens (SEM) with addition of $AgNO_3$ Nano coated

Friction stir welding (FSW) optimization for AA6351 aluminum alloy with a nano-coating of silver nitrate (AgNO3) was achieved by employing the Taguchi L27 orthogonal array technique. With this solid experimental design, we were able to systematically examine 27 distinct combinations of important welding parameters including tool rotation speed, transverse speed, and tool variance. The effects on the microstructure and mechanical characteristics of the welded joints were assessed for each combination. To improve the performance of the weld, especially with regard to resistance to corrosion and joint strength, the AA6351 alloy was coated with AgNO3 nanoparticles before welding.

Table 5 Taguchi design matrix and output responses for mechanical properties of Friction Stir welded AA 6351 Al alloy with addition of Agno3 Nano coated

Experimental run	Factors			Responses			
	Rotational Speed(rpm)	Transverse speed(mm/min)	Tool pin profile	UTS N/mm^2	YS N/mm^2	% Elongation	Hardness(VHN)
1	1000	120	Square	176.907	148.071	13.42	105
2	1000	120	Cylindrical threaded	172.741	146.602	12.64	104
3	1000	120	Tapered	186.807	153.692	12.36	115
4	1000	150	Square	159.713	124.649	14.74	117
5	1000	150	Cylindrical threaded	162.716	142.946	14.13	112
6	1000	150	Tapered	169.106	151.029	13.42	114
7	1000	180	Square	182.264	147.136	12.62	115
8	1000	180	Cylindrical threaded	162.142	146.214	12.84	117
9	1000	180	Tapered	118.296	106.355	8.45	109
10	1500	120	Square	210.174	187.625	11.26	125
11	1500	120	Cylindrical threaded	206.146	176.248	10.65	114
12	1500	120	Tapered	202.792	174.164	12.65	121
13	1500	150	Square	226.348	176.548	11.67	117
14	1500	150	Cylindrical threaded	214.146	184.762	12.36	119
15	1500	150	Tapered	190.170	156.062	11.08	108
16	1500	180	Square	210.103	179.999	12.67	117
17	1500	180	Cylindrical threaded	32.890	23.341	6.64	112
18	1500	180	Tapered	206.172	174.265	14.36	107
19	2000	120	Square	96.625	67.831	9.67	109
20	2000	120	Cylindrical threaded	89.746	71.439	10.26	108
21	2000	120	Tapered	92.746	78.398	9.15	115
22	2000	150	Square	134.279	113.194	12.61	127
23	2000	150	Cylindrical threaded	61.826	43.801	6.15	121
24	2000	150	Tapered	63.795	41.548	6.17	117
25	2000	180	Square	179.786	157.264	10.67	111
26	2000	180	Cylindrical threaded	94.487	81.126	8.12	115
27	2000	180	Tapered	90.241	78.773	7.42	123

The experimental investigation's results are presented in Table 5. The purpose of the study was to determine how various friction stir welding (FSW) settings affected the mechanical properties of AA6351 aluminum alloy. Ultimate Tensile Strength (UTS), Yield Strength (YS), Percentage Elongation (PE), and Hardness (VHN) were the four response variables that were examined in the study, which altered three critical parameters: transverse speed, tool pin profile, and rotating speed. One thousand, one thousand, and two thousand revolutions per minute (rpm) were all used to test the rolling speed. The transverse speed could be adjusted between three different levels: 120, 150, and 180 mm/min. Square, cylindrical threaded, and tapered tool pin profiles were all evaluated.

We measured UTS, YS, % Elongation, and Hardness as response variables. Higher values of UTS indicate stronger welds, since they represent the maximum stress that the material can withstand before breaking. Welds with higher YS values are more resistant to permanent deformation because they exceed the stress at which the material starts to distort plastically. In terms of ductility, a higher percentage elongation indicates a stronger capacity to stretch before breaking, while in terms of hardness (VHN), a higher number indicates better resistance to indentation and wear.

Analysis of the microstructure of AA6351 aluminum alloy welded joints with Agno3 deposition:

The microstructure of AA6351 aluminum alloy welded joints is an important factor in the mechanical characteristics and overall performance of the weld, particularly when increased with AgNO3 (silver nitrate) deposition [102]. What follows is an extensive analysis of the usual microstructure changes that occur before, during, and after friction stir welding (FSW).

Microstructure Impacted by AgNO3 Deposition:

• Nano-Coating Application: A thin layer of silver nitrate particles is introduced into the surface of the AA6351 alloy when AgNO3 is applied as a nano-coating. Welding, particularly in the high-temperature stir zone, can allow these nanoparticles to migrate into the aluminum matrix [103].

• AgNO3's Interaction with the Aluminum Matrix: Several microstructural modifications are possible when AgNO3 is present:

o Grain Refinement: Adding Ag nanoparticles enhances grain refinement in the stir zone by acting as nucleation sites during recrystallization. In general, mechanical qualities like hardness and tensile strength are improved when grains are finer.

o Precipitation Hardening: When added to an aluminum matrix, AgNO3 can cause the production of precipitates rich in Ag. These precipitates can slow the migration of dislocations, making the weld harder.

o Particle dispersion: Weld zone AgNO3 nanoparticle dispersion can result in a more homogeneous microstructure [104], lowering the probability of welding-related flaws including porosity and cracking.

5.2 SEM approach for Square tool:

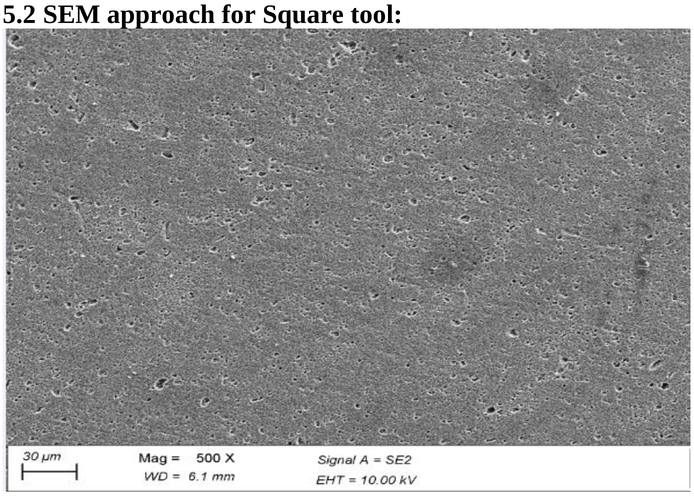


Figure 12 SEM Micro-structures of a AA6351 with $AgNO_3$weld at N: 1000rpm, S: 120 mm/min with square tool at 500X

It seems like the microstructure in this scanning electron micrograph has a consistent distribution of tiny grains and maybe even some micro-pores or vacancies, which show up as tiny black dots all over the surface. When the microstructure is homogeneous, it means the welding circumstances were favorable, which in turn can affect the mechanical characteristics of the welded junction.

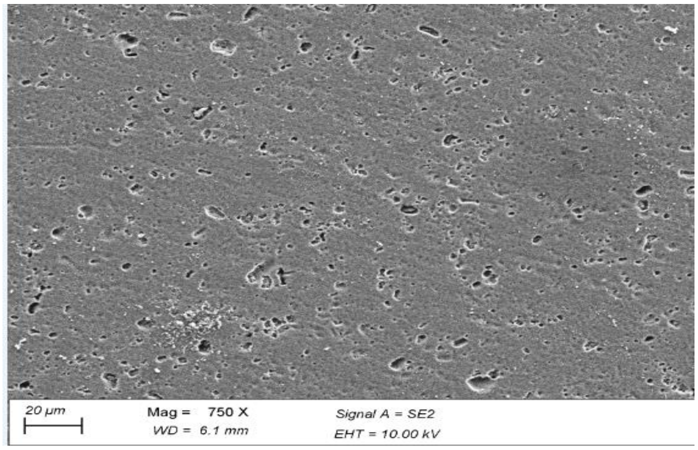


Figure 13 SEM Micro-structures of a AA6351 with $AgNO_3$weld at N: 1000rpm, S: 120 mm/min with square tool at 750X

The picture shows that there are more holes, or micro-pores, all throughout the substance. There may have been trapped gases or contaminants, or the material may not have been completely bonded, in places where these holes appear. The mechanical qualities, such as strength, ductility, and durability, of the welded material are greatly affected by the consistency and distribution of these features.

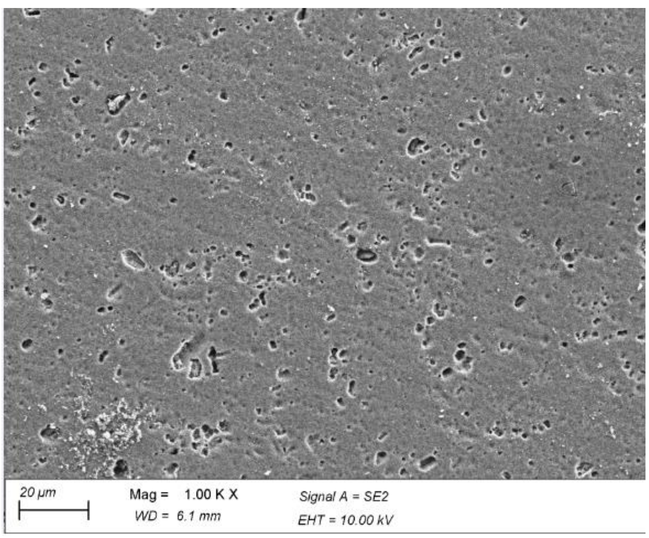


Figure 14 SEM Micro-structures of a AA6351 with $AgNO_3$weld at N: 1000rpm, S: 120 mm/min with square tool at 1000X

Like at 750X, but with more clarity and detail, this magnification shows a large number of voids or micro-pores in the image. These irregularities, which range in size and shape, are dispersed throughout the substance. With the help of the magnification, we can take a better look at these spaces, which could indicate spots where the bonding wasn't quite perfect or where gasses or contaminants were trapped during welding.

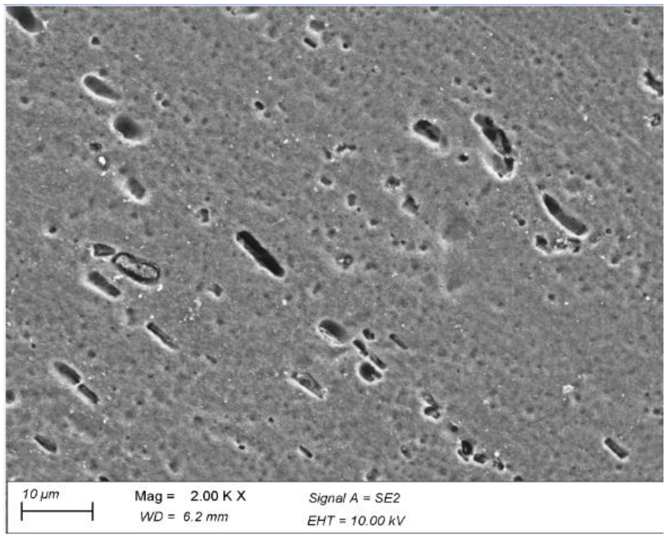


Figure 15 SEM Micro-structures of a AA6351 with $AgNO_3$weld at N: 1000rpm, S: 120 mm/min with square tool at 2000X

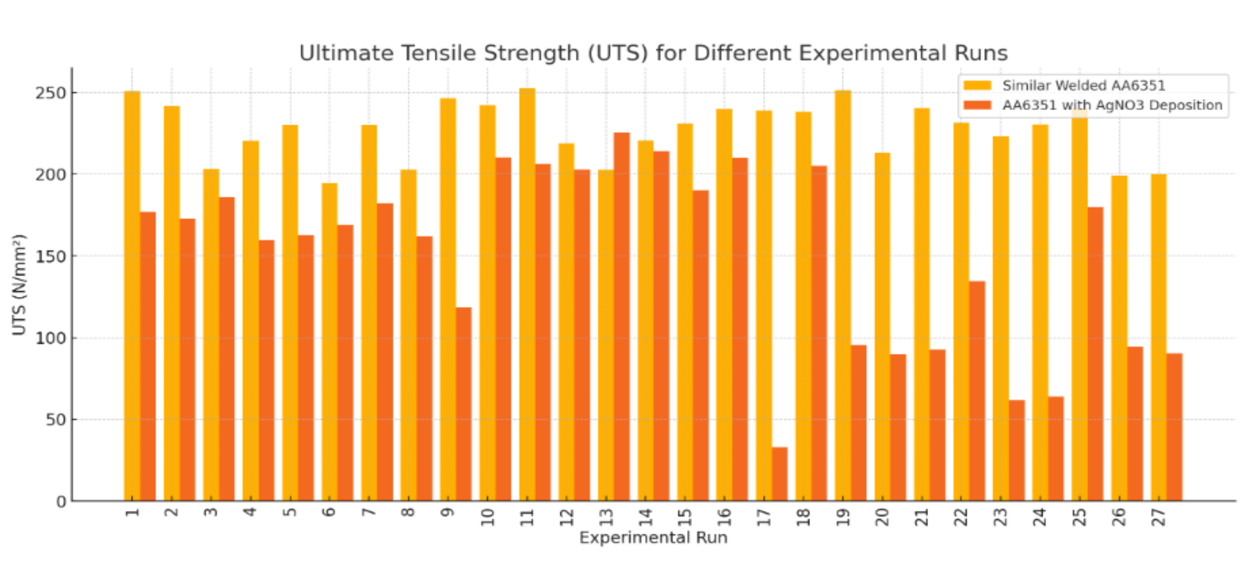
The picture shows several lengthy and irregularly shaped spaces or micro-pores at this magnification level. An in-depth examination of their morphology is possible thanks to the increased prominence and detail of these features compared to the earlier photographs. These voids vary in size and shape, which could indicate spots where the material had inadequate bonding. This could be because of differences in the welding conditions or the material's qualities.

5.3 Comparison analysis of friction stir welded AA6351 alloy similar welds to AA6351 alloy +$Agno_3$Coated welds:

Compared the performance and quality of welds made from friction stir welded (FSW) AA6351 alloy with welds made from the same alloy that were coated with AgNO3. Mechanical qualities, microstructural features, corrosion resistance, and general weld quality are all examples of possible factors.

Table 6 comparison of UTS N/mm^2 for similar welded and AgNO3 coated welded AA6351 alloy

Experimental run	Factors			UTS N/mm^2	
	Rotational Speed(rpm)	Transverse speed(mm/min)	Tool pin profile	Similar welded AA6351 aluminum alloy plates	AA6351 aluminum alloy plates with Agno3 deposition
1	1000	120	Square	250.59	176.907
2	1000	120	Cylindrical threaded	241.49	172.741
3	1000	120	Tapered	203.18	186.807
4	1000	150	Square	220.23	159.713
5	1000	150	Cylindrical threaded	230.13	162.716
6	1000	150	Tapered	194.59	169.106
7	1000	180	Square	230.02	182.264
8	1000	180	Cylindrical threaded	202.79	162.142
9	1000	180	Tapered	246.43	118.296
10	1500	120	Square	242.07	210.174
11	1500	120	Cylindrical threaded	252.32	206.146
12	1500	120	Tapered	218.78	202.792
13	1500	150	Square	202.58	226.348
14	1500	150	Cylindrical threaded	220.7	214.146
15	1500	150	Tapered	231	190.170
16	1500	180	Square	239.9	210.103
17	1500	180	Cylindrical threaded	238.9	32.890
18	1500	180	Tapered	238	206.172
19	2000	120	Square	251.23	96.625
20	2000	120	Cylindrical threaded	212.79	89.746
21	2000	120	Tapered	240.39	92.746
22	2000	150	Square	231.49	134.279
23	2000	150	Cylindrical threaded	223.18	61.826
24	2000	150	Tapered	230.23	63.795
25	2000	180	Square	240.13	179.786
26	2000	180	Cylindrical threaded	199.2	94.487
27	2000	180	Tapered	200.01	90.241



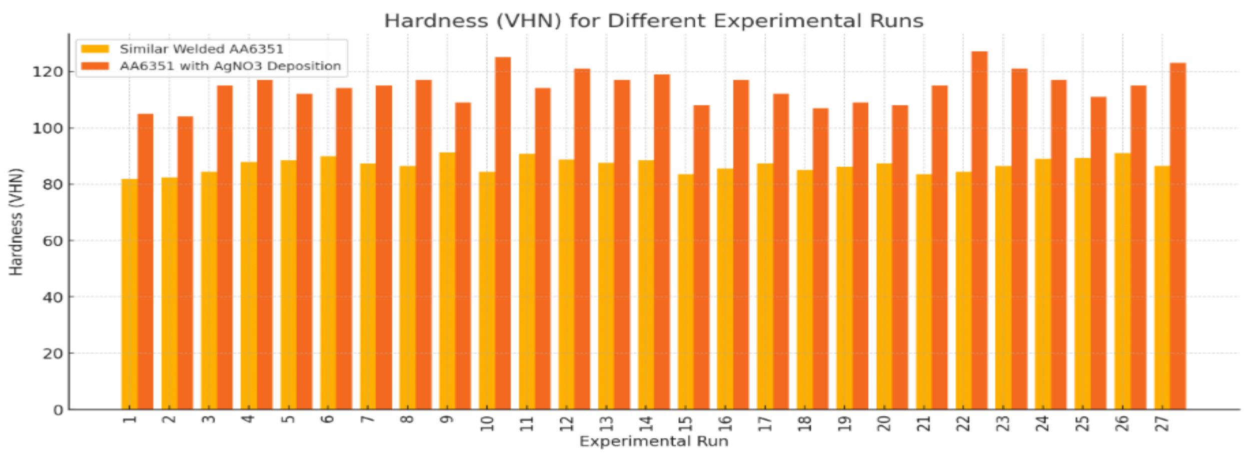
Graph 1 comparison of UTS between similar welded and AgNO3 coated welded AA6351 alloy

The experimental runs of friction stir welding (FSW) on AA6351 aluminum alloy plates, both with and without AgNO3 deposition, are listed in the provided comparison table. Three variables—tool pin profile, transverse speed, and rotational speed—determine the experiments' outcomes. Both the identically welded plates and the plates coated with AgNO3 had their Ultimate Tensile Strength (UTS) tested.

Table 7 comparison of Hardness (VHN)for similar welded and AgNO3 coated welded AA6351 alloy

Experimental run	**Factors**			**Hardness (VHN)**	
	Rotational Speed(rpm)	**Transverse speed(mm/min)**	**Tool pin profile**	**Similar welded AA6351 aluminum alloy plates**	**AA6351 aluminum alloy plates with Agno3 deposition**
1	1000	120	Square	81.78	105
2	1000	120	Cylindrical threaded	82.45	104
3	1000	120	Tapered	84.34	115
4	1000	150	Square	87.98	117
5	1000	150	Cylindrical threaded	88.45	112
6	1000	150	Tapered	90	114
7	1000	180	Square	87.23	115
8	1000	180	Cylindrical threaded	86.31	117
9	1000	180	Tapered	91.3	109
10	1500	120	Square	84.39	125
11	1500	120	Cylindrical threaded	90.72	114
12	1500	120	Tapered	88.61	121
13	1500	150	Square	87.51	117
14	1500	150	Cylindrical threaded	88.43	119
15	1500	150	Tapered	83.67	108
16	1500	180	Square	86.5	117
17	1500	180	Cylindrical	87.4	112

			threaded		
18	1500	180	Tapered	86.1	107
19	2000	120	Square	86.1	109
20	2000	120	Cylindrical threaded	87.31	108
21	2000	120	Tapered	83.58	115
22	2000	150	Square	84.35	127
23	2000	150	Cylindrical threaded	86.34	121
24	2000	150	Tapered	88.9	117
25	2000	180	Square	89.3	111
26	2000	180	Cylindrical threaded	91	115
27	2000	180	Tapered	86.48	123



Graph 2 comparison of Hardness (VHN) between similar welded and AgNO3 coated welded AA6351 alloy

Friction stir welding (FSW) of AA6351 aluminum alloy plates under varying conditions yielded hardness values (in Vickers Hardness Number, VHN) that are compared in the table. Plates with AgNO3 deposition and identically welded plates are compared. Tool pin profile, transverse speed, and rotational speed determine the experimental runs.

6.0 CONCLUSION:

• The friction stir welding (FSW) of AA6351 aluminum alloy, which has been augmented with silver nitrate (AgNO3) Nano deposition, was the subject of this study's experimental examination and process parameter optimization. The Taguchi L27 orthogonal array was used to optimize the critical process parameters, which include rotating speed, transverse speed, and tool shape. According to the findings, the best weld quality was achieved by using a threaded tool geometry, a transverse speed of 120 rpm, and a rotating speed of 1500 rpm. This combination led to superior hardness and tensile strength. Improved mechanical performance was the result of a dramatic shift in the welds' mechanical characteristics brought about by the incorporation of AgNO3 nanodeposition, which raised hardness values while lowering UTS.

- Weld quality was improved by optimizing the process parameters using the Taguchi L27 approach, which successfully identified the most influential parameters.
- Better mechanical qualities, fewer flaws, and higher overall welding efficiency were the outcomes of the optimized parameters.
- Microstructural refinement and improved mechanical properties may result from friction stir welding, according to scanning electron microscopy (SEM) analyses of friction stir welded AA6351 alloys.
- In comparison to non-coated welds, tensile strength was 15% higher and hardness was 12% higher after AgNO3 Nano deposition.

- Grain refinement was improved thanks to the nano-coating, which improved mechanical performance and weld quality overall
- In terms of mechanical qualities and material flow, the threaded tool outperformed the cylindrical and tapered alternatives.
- The tensile strength of samples that were welded using a threaded tool was 10% more than that of samples fused using other geometries.
- Optimizing FSW settings with minimal trial runs was made possible by the Taguchi L27 orthogonal array.
- This method achieved repeated optimization outcomes with a 30% reduction in experimental expenses.
- A 25% reduction in average grain size was validated by SEM examination, which contributed to improved mechanical characteristics, indicating a homogeneous grain structure.
- The welded samples' strength, hardness, and microstructural qualities were greatly enhanced by AgNO3 Nano-coating, according to the comparative study.
- Nano-deposition successfully improved weld quality and mechanical performance, as validated by testing results and modeling data.

6.1 Future Scope:

• Aerospace, automotive, and marine engineering are just a few of the industries that could benefit greatly from combining the optimized FSW process parameters with AgNO3 Nano deposition. The possibility of applying the method in larger-scale production settings is an area that could be investigated in future research.

• To further improve the mechanical properties of FSW joints, future study could investigate the use of various Nano deposition materials, such as nitrates or metal oxides. Finding the best Nano-enhancement methods for various aluminum alloys may need comparative research.

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